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A REVIEW OF MILLIMETRE WAVE DEVICES

Author: A J Grant

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Author: A J Grant

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SUMMARY

↪ A review is given of recent improvements in the performance of power sources in the millimetre band, 30-300 GHz, corresponding to free space wavelengths from 1 cm down to 1 mm. Vacuum tube devices of interest include the magnetron, the TWT, the carcinotron or backward wave oscillator, the gyrotron or cyclotron resonance maser, and the recently discovered orbitron, which was demonstrated using an empty aluminium beer-can. Solid state sources have continued to make progress upwards in both frequency and power. Transferred electron devices using InP have produced 126 mW at 90 GHz, a level suitable for local oscillator applications, while Si impatts have demonstrated peak power of 13W at 94 GHz with 8% efficiency. The tunnelt diode, a variation of the impatt in which tunnelling replaces avalanching, has shown useful power above 300 GHz. ↪

Notes from an invited talk given at the Conference on Millimeter and Far-infrared spectroscopy organised by the British Radio frequency Spectroscopy Group at St Andrews University, April 1981.

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A REVIEW OF MILLIMETRE WAVE POWER SOURCES

A J Grant

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ACKNOWLEDGEMENTS

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1 INTRODUCTION

A review is given of the performance of power sources in the millimetre band, 30-300 GHz, corresponding to free space wavelengths from 1cm down to 1mm. This frequency band has seen a marked increase in activity in the past few years, due in large measure to advances in device performance which now offer the prospect of systems with significant military and civil applications.

Devices which produce power at millimetre wavelengths may be considered in two main categories, electron tubes and solid state devices.

2 MILLIMETRE WAVE ELECTRON TUBES

Vacuum tube sources all convert part of the kinetic energy of an electron beam into electromagnetic energy, using various mechanisms. We deal first with tubes in which the E.M wavelength is related to a resonant cavity or a periodic slow wave structure. Examples of this type of device are magnetrons, klystrons, extended interaction oscillators, travelling wave tubes and backward wave oscillators. (Table 1).

2.1 Crossed Field Tubes

2.1.1 Magnetrons

Magnetrons are crossed field devices, with $\underline{E} \perp \underline{B}$, where \underline{E} is the electric field and \underline{B} the magnetic field. Electrons are emitted from the cathode and in travelling to the anode excite the resonant cavities and give up energy to the RF field. Magnetrons are capable of high peak power but low duty cycles and hence low average power due to the difficulty of heat dissipation. At millimetric wavelengths the cathode area is small, and life is limited by the high emission current density and by back bombardment. A rising sun anode design is used to control the operating mode.

A recently developed 95 GHz EMV magnetron is capable of 3kW peak power, 0.6W mean power and has an expected life of 750 hours. This device costs about £6K plus power supplies, and weighs about 2kg. This device probably represents the upper frequency limit of current magnetron technology.

2.2 Linear Beam Tubes

Linear beam tubes have $\underline{E} \parallel \underline{B}$, and consist of an electron gun, an interaction region where the electron beam is confined magnetically and interacts with a slow wave structure, and a collector. The electron beam diameter is smaller than the output wavelength, and thus the fabrication of such tubes above 90 GHz, where $\lambda \leq 3\text{mm}$, becomes extremely difficult. The available power levels also fall correspondingly.

2.2.1 Reflex Klystrons

In this tube, the electron beam passes once through the resonant cavity and is then reflected back through the interaction gap before being collected on the finely machined R.F structure. This limits the power levels at which these tubes can operate to about 1W at 50 GHz, 10 mW at 200 GHz, and 10 mW at 200 GHz. Reflex klystrons are likely increasingly to be replaced in local oscillators and other low power applications by solid state devices such as transferred electron oscillators and impatts.

2.2.2 Extended Interaction Oscillators

The EIO is a single cavity tube which gives much greater CW power, since the collector is separate from the RF structure, and the device is not limited by the power dissipation capability of the RF elements. The EIO employs a separate cathode which allows lower

current density and a resulting life expectancy of thousands of hours. The tube offers about 4% mechanical and 0.2% electrical tuning. Power output available is 150W CW or 10kW peak at 75 GHz and 20W CW, or 100 W peak at 150 GHz. Extended interaction amplifiers have recently been offered for sale at 95 GHz with a likely cost of order £20K. These devices give 2.3 kW peak output at 33 dB gain and use samarium cobalt permanent magnets to achieve low volume and weight.

EIOs and EIAs are under development up to 280 GHz with an expected power output of order 1W. These devices will have a new gridded cathode in which a control grid is fabricated on the cathode, making the devices easier to pulse.

2.2.3 Travelling Wave Tubes

Helix TWTs are capable of moderate power levels at low efficiency, due to the difficulty of heat extraction from the helix, which inevitably intercepts a small proportion of the beam energy. Power of order 100 W mean at 50 GHz can be achieved.

Coupled cavity TWTs offer higher output power, with the heat generated in the final cavity the limiting factor. Another critical factor is the beam confinement. Alternating permanent magnets of samarium cobalt may be used to achieve weight reduction, since the electrons are obligingly unconcerned by the sense of the axial magnetic field. The highest power levels are achieved with solenoid magnets, with 6 kW pulsed at 94 GHz demonstrated, but the solenoid requires 300 V at 30 A.

2.2.4 Backward Wave Oscillators

In BWOs the microwave energy (or group velocity) moves in the opposite direction to the electron beam. The phase velocity is approximately equal to the electron velocity, and may therefore be varied by changing the beam energy. BWOs are thus capable of broadband operation with electrical tuning, though at relatively modest power levels. Power output is 5-15 W at 69-71 GHz; 0.3 - 4W at 88-92 GHz; 0.1 - 1W at 270-290 GHz. Russian tubes have operated up to 1200 GHz, the highest frequency known for a vacuum tube, with verbal reports of tubes operating up to 2000 GHz (Military Electronics and Countermeasures, June 1980).

2.3 Fast Wave Tubes

Fast wave tubes utilise the interaction of a periodic electron beam with an RF fast wave in a low loss waveguide mode. The tube diameter is greater than one wavelength, so that the beam diameter and power density constraints which apply to slow wave tubes are avoided. Examples of fast wave tubes are the gyrotron, the peniotron and the ubitron.

2.3.1 Gyrotrons

Gyrotrons have been the subject of intense interest in the past few years, and Russian devices have demonstrated state of the art power levels for thermionic tubes, with 1MW at 45 and 100 GHz.

The gyrotron is based upon the electron cyclotron effect, where an electron in a dc magnetic field performs orbits with an angular frequency

$$\omega = \frac{eB}{\gamma m} \quad \text{where } e/m \text{ is the electron charge/mass,}$$

γ the relativistic mass factor, B is the axial magnetic flux density and n is the harmonic number. In the beam, most of the electron energy is required to be transverse to the tube axis, and it is this energy which is converted with high efficiency into radiation.

In the gyrotron, angular bunching of the electron beam occurs because of the relativistic mass effect and when correctly tuned, the electrons give up their transverse energy to the TE_{01} RF field. ($n = 1$). A significant limitation is the high value of magnetic field required for a gyrotron, given by

$$B \text{ (kG)} = 0.35 \frac{\gamma f}{n} \text{ (GHz)}$$

For fundamental operation ($n = 1$), the required field is 13 kG at 35 GHz and 34 kG at 94 GHz. This necessitates the use of superconducting magnets at 60 GHz or higher. Harmonic operation ($n > 2$) has been demonstrated, but results in lower efficiency.

A major field of application for gyrotrons has been for electron cyclotron resonance heating of plasmas in fusion research machines. A 28 GHz 200 kW pulsed device is in use at Culham. At higher frequencies CW operation has been reported in the USSR at 333 GHz, with 1.5 kW output, $n = 2$ and 6% efficiency. A gyro TWT amplifier is under development in the USA at 94 GHz, with a superconducting solenoid and 10 kW output.

2.3.2 Peniotron

The peniotron, first proposed in Japan, uses a cylindrical electron beam which interacts with a longitudinally ridged waveguide. The angular frequency is twice the fundamental gyrotron frequency, and the predicted conversion efficiency for the transverse beam energy is nearly 100%. A 1 kW 94 GHz amplifier is under development in the USA.

2.3.3 Ubitron

The ubitron uses a periodically (spatially) varying magnetic field to produce a spatially undulating electron beam which interacts with the RF field in a circular waveguide. A ubitron amplifier built in the early 1960s produced 150 kW at 54 GHz with 5% efficiency. More recently, the operating principles have been applied to free electron lasers using relativistic electron beams. These machines are the subject of a later paper at this Conference.

2.3.4 Orbitron

A fascinating new device reported recently has been named the orbitron. The prototype consists of an empty aluminium beer can with a positive wire running centrally down the cylindrical axis. A high voltage pulse ionises the low pressure air and produces electrons which are attracted to the positive central wire. Those electrons with some transverse angular momentum begin to orbit the anode wire, with their electrical attraction opposed by centrifugal force. This device has produced pulses of microwave power up to 54 GHz. Multiwire structures are under investigation and a parallel plate structure has been tried successfully. No theoretical model has yet appeared for this device, but we shall no doubt hear more of it in the future, as it offers the potential advantage of electrostatic confinement, with no magnetic field required.

3 SOLID STATE POWER SOURCES

The power available from solid state devices is about 2 orders of magnitude below that from electron tubes at a given frequency and falls rapidly with increasing frequency, as the volume of the active region decreases to a few microns times a few tens of microns squared. Three terminal devices such as field effect transistors are not yet available in the millimetre band, and practical devices are limited to 2 terminal devices of two main types, the transferred electron oscillators or Gunn diodes, and the avalanche diodes or impatts.

3.1 Transferred electron Devices

TEOs depend on a semiconductor having a suitable conduction band structure, with a high mobility central valley and a lower mobility higher energy or satellite valley. A negative resistance is produced by the exchange of hot electrons between these valleys in a strong applied electric field. GaAs and InP possess a suitable conduction band structure, with InP expected to have superior properties for high frequency devices.

GaAs TEOs are now widely available from a number of companies, with 150 mW at 2% efficiency at 60 GHz, and 30 mW at 94 GHz at less than 1% efficiency. Current interest is centred on InP for higher efficiency and higher power TEO devices. Recent results include 240 mW pulsed at 60 GHz at RSRE and 126 mW C.W at 4.7% efficiency at 90 GHz at Varian. Power of order 1 mW has been detected at RSRE at 140 GHz from an InP TEO, which is the highest known frequency for a TE device.

Theoretical device modelling at RSRE has led to a new proposal for higher power TE devices in the millimetre band. In this approach, thicker epitaxial layers are used and simultaneously DC biased and RF pumped at a frequency f , say 50 GHz. The device is expected to exhibit a non-sinusoidal oscillation, absorbing power at f , and by the use of a suitable circuit, to produce power at $2f$. Mean power of order 1W at 100 GHz is expected with this new device, an active bulk multiplier, due to the greater active volume.

3.2 Impatt Diodes

Impact avalanche transit time or impatt diodes may be produced using Si, GaAs and InP. Power levels at least an order of magnitude greater than TEOs are possible, although the noise levels are higher.

Silicon impatts have demonstrated the highest power levels, with 13W peak at 8% efficiency at 94 GHz and 9.2 W at 140 GHz from double drift $p^{+}pnn^{+}$ structures reported by Hughes. These give higher impedance and greater power than single drift $p^{+}nn^{+}$ structures, due to the presence of two drift regions. This is a very difficult technology with active regions less than 1 μm thick and substrates must be thinned below 10 μm to minimise parasitic resistance due to skin effect above 100 GHz. Silicon has a strong advantage in possessing the highest thermal conductivity of suitable semiconductors, allowing more efficient heat extraction via diamond or copper heat sinks. Power combining techniques have demonstrated 40W at 94 GHz from 4 devices in a rectangular resonator.

In the UK, GEC have achieved 31W peak from a single DD Si device at 35 GHz at about 5% efficiency, using a copper heatsink and at higher frequencies Plessey have demonstrated 400 mW at 12% efficiency at 80 GHz.

At higher frequencies 0.5 W pulsed has been reported at 225 GHz, and it is likely that useful power levels will be achieved to 300 GHz at least.

3.3 Tunnets

In the tunnnett diode carriers are produced in the drift region by tunnelling, rather than avalanching as in the impatt. This device was proposed by Nishizawa in 1958, and represents the limit of high frequency impatt operation, where thin active regions and very high electric fields will inevitably lead to tunnelling injection. However in the range 100-300 GHz both impatts and tunnnetts can be produced, with GaAs as the preferred material due to its lower ionisation rates. The tunnnett is expected to operate at a lower bias voltage than an impatt, and to give lower noise. The tunnnett structure is $p^{+}n^{+}in^{+}$ or $p^{+}nn^{+}$, with the n^{+} region ideally 100A thick and having a peak electric field of $10^6 v.cm^{-1}$. GaAs devices grown by liquid phase epitaxy and having an active layer thickness of 0.4 μm have produced pulsed power of 10 mW at 338 GHz. The tunnnett has lower efficiency than the impatt, and is likely to be useful in local oscillator and other low power applications.

4 CONCLUSIONS

There are other intriguing possibilities for the generation of power in the millimetre band. Cyclotron emission has been demonstrated in semiconductors, and maser oscillations between Rydberg states in alkali metal atom beams have been observed. Another possibility was suggested in a paper at the Infra-red and Millimetre Wave Conference in Wurzburg in 1980. This involved the generation of pulsed photo diode currents at millimetre wave lengths which couple into a wave guide. The photo diode currents are generated in a semiconductor by the beating of two CO_2 or CO lasers operating at slightly different frequencies. Developments of these and other ideas in both solid state devices and in thermionic vacuum tubes are likely to continue in the future.

ACKNOWLEDGEMENTS

I gratefully acknowledge the invaluable assistance of colleagues at RSRE, Plessey, GEC, EMI-Varian, Thomson-CSF and Hughes Aircraft Company in preparing the material for this paper.

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- Figure 1 Millimetre Wave Vacuum Tubes
- Figure 2 A rising sun magnetron anode structure is used to control the device mode. In the 95 GHz EEV device the anode is stamped 'hobbed' - from a solid copper billet.
- Figure 3 M5163 EEV 94 GHz Magnetron capable of 3 kW peak 0.6W mean.
- Figure 4 EEV 95 GHz magnetron using samarium cobalt magnets for reduced volume and weight.
- Figure 5 Schematic of an extended interaction oscillator tube in which the cathode, interaction and collector structures are separate.
- Figure 6 A 95 GHz extended interaction oscillator capable of 2.3 kW peak output at 32 dB gain. This device uses SmCo magnets.
- Figure 7 The power output versus frequency for EIOs and EIAs.
- Figure 8 The Hughes 915H Q-band TWT, capable of 250W CW between 43-45 GHz.
- Figure 9 The Varian 35 GHz travelling wave tube, which has demonstrated 30 kW peak and 9 kW mean.
- Figure 10 Average power versus frequency for current helix, ppm coupled cavity and solenoid focussed coupled cavity TWTs.
- Figure 11 A backward wave oscillator capable of 1-2W at 280 GHz \pm 3%.
- Figure 12 A backward wave oscillator giving between 5-10 mW power at 360 GHz \pm 10%.
- Figure 13 Summary of the performance of various vacuum tubes as a function of frequency.
- Figure 14 Schematic showing the principle of operation of the gyrotron tube, in which the transverse energy of a relativistic electron beam undergoing cyclotron orbits couples to an EM wave.
- Figure 15 Schematic of a gyrotron amplifier showing the cathode which generates the hollow electron beam, the interaction region and the collector.
- Figure 16 The 28 GHz pulsed gyrotron in use at Culham.
- Figure 17 Performance characteristics of the Culham gyrotron.
- Figure 18 Double ridged wave guide structure of the peniotron tube which is predicted to have a very high conversion efficiency for transverse beam energy.
- Figure 19 Schematic of the orbitron, which uses a low pressure gas discharge and has demonstrated power up to 50 GHz.
- Figure 20 The Orbitron was demonstrated using an empty aluminium beer can and has the advantage of using electrostatic fields only with no magnets required.

- Figure 21 Laboratory CW Power performance of microwave diodes vs. frequency.
- Figure 22 Power output vs. frequency for the two principal types of solid state device:- Si double drift impatt diodes on diamond heat sinks and InP and GaAs transverse electron diodes on copper heat sinks.
- Figure 23 An extended frequency performance predicted for InP devices in multiplier mode should lead to gain and power above 1W in the millimetre band.
- Figure 24 The doping and electric field profile for double drift impatt devices.
- Figure 25 Sketch of a 4-chip 60W pulsed impatt diode assembly.
- Figure 26 Power combiner using rectangular resonator.

SLOW WAVE TUBES

Crossed Field Tubes E 1 B

Magnetrons

Crossed field amplifier

Linear Beam Tubes E 1 B

Klystrons/Extended Interaction Oscillators

Travelling Wave Tubes

Backward Wave Oscillators

FAST WAVE TUBES

Gyrotron (cyclotron resonance maser)

Peniotron

Ubitron (free electron laser)

Orbitron

FIGURE 1 MILLIMETRE WAVE VACUUM TUBES

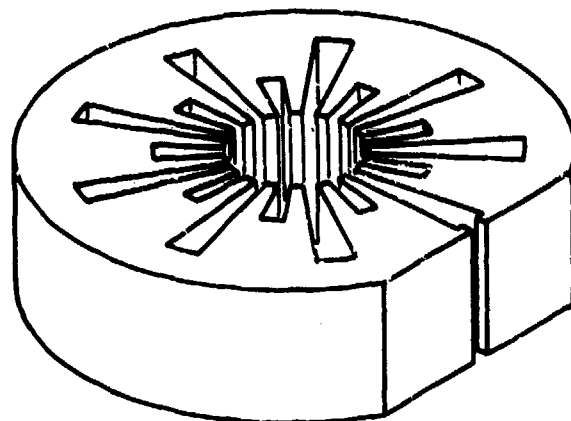


FIGURE 2 A RISING SUN MAGNETRON ANODE STRUCTURE IS USED TO CONTROL THE DEVICE MODE. IN THE 95 GHz EEV DEVICE THE ANODE IS STAMPED 'HOBBED' - FROM A SOLID COPPER BILLET

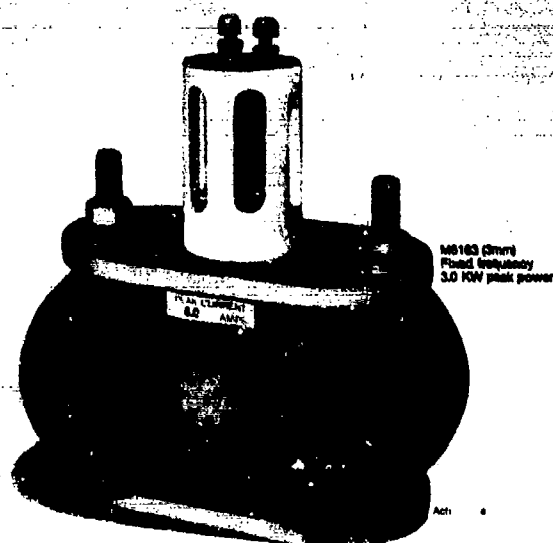


FIGURE 3 M8163 EEV 94 GHz MAGNETRON CAPABLE OF 3 kW PEAK 0.6W MEAN

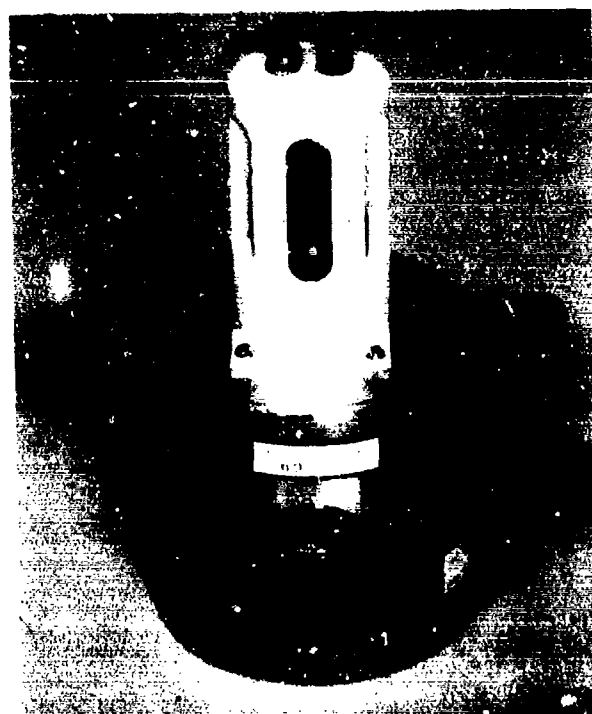


FIGURE 4 EEV 95 GHz MAGNETRON USING SAMARIUM COBALT MAGNETS FOR REDUCED VOLUME AND WEIGHT

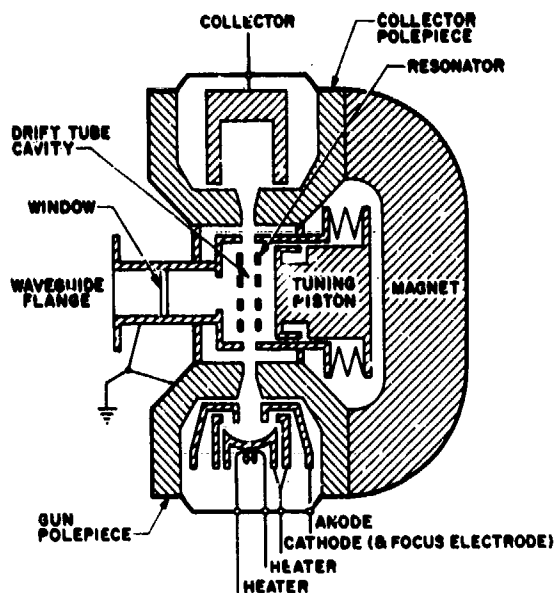
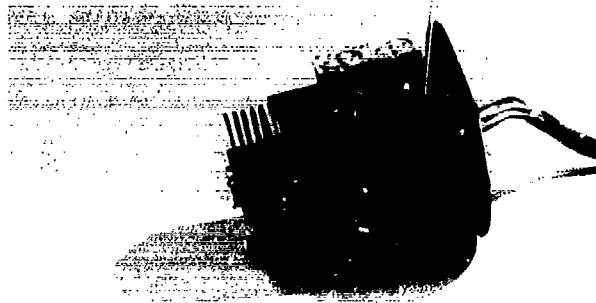


FIGURE 5 SCHEMATIC OF AN EXTENDED INTERACTION OSCILLATOR TUBE IN WHICH THE CATHODE, INTERACTION AND COLLECTOR STRUCTURES ARE SEPARATE



Enhance target detection.
Varian Canada introduces
the first 95 GHz EIA.

FIGURE 6 A 95 GHz EXTENDED INTERACTION OSCILLATOR CAPABLE OF 2.3 kW PEAK OUTPUT AT 32 dB GAIN. THIS DEVICE USES SmCo MAGNETS

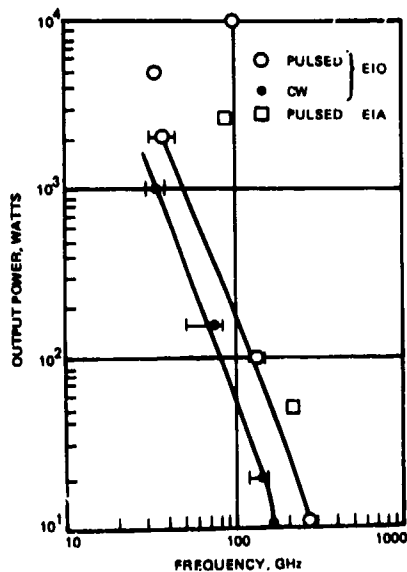


FIGURE 7 THE POWER OUTPUT VERSUS FREQUENCY FOR EIOs AND EIAs

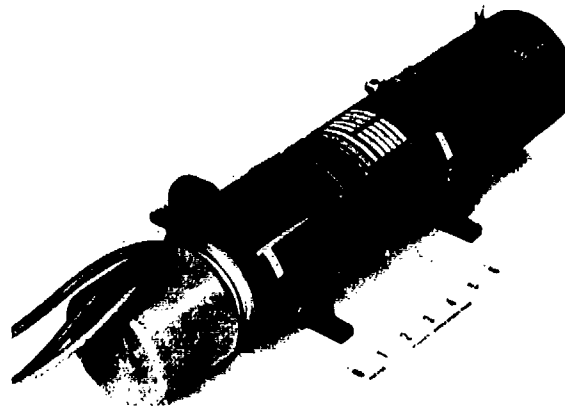


FIGURE 8 THE HUGHES 915H Q-BAND TWT, CAPABLE OF 250W CW BETWEEN 43-45 GHz

E1585

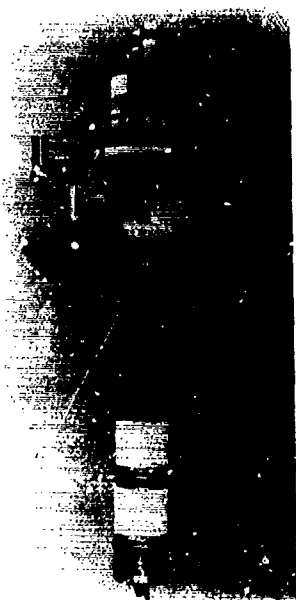


FIGURE 9 THE VARIAN 35 GHz TRAVELLING WAVE TUBE, WHICH HAS DEMONSTRATED 30 kW PEAK AND 9 kW MEAN

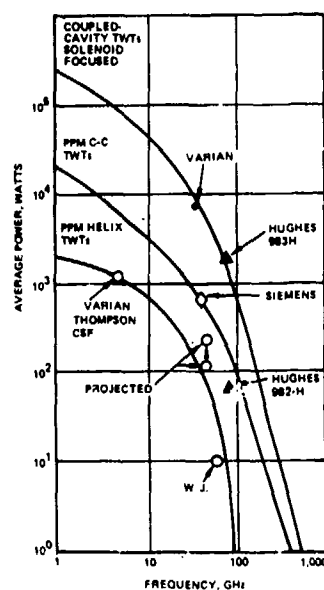


FIGURE 10 AVERAGE POWER VERSUS FREQUENCY FOR CURRENT HELIX, PPM COUPLED CAVITY AND SOLENOID FOCUSED COUPLED CAVITY TWTs

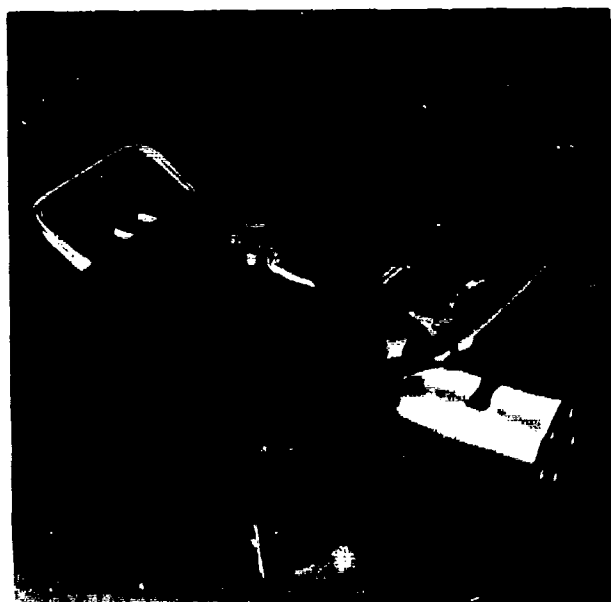


FIGURE 11 A BACKWARD WAVE OSCILLATOR CAPABLE OF 1-2W AT 280 GHz \pm 3%

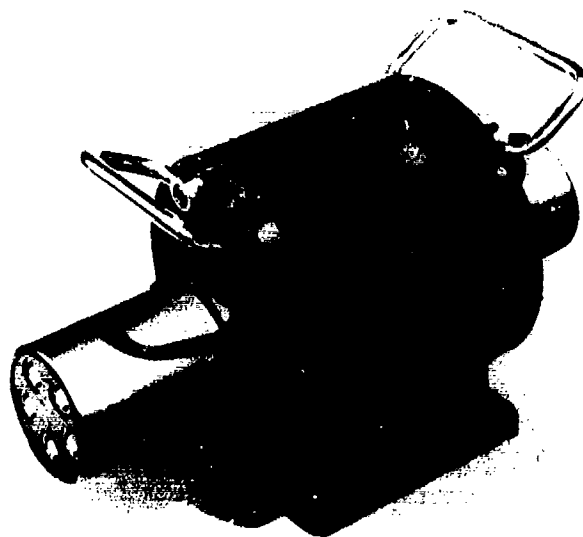


FIGURE 12 A BACKWARD WAVE OSCILLATOR GIVING BETWEEN 5-10 mW POWER AT 360 GHz \pm 10%

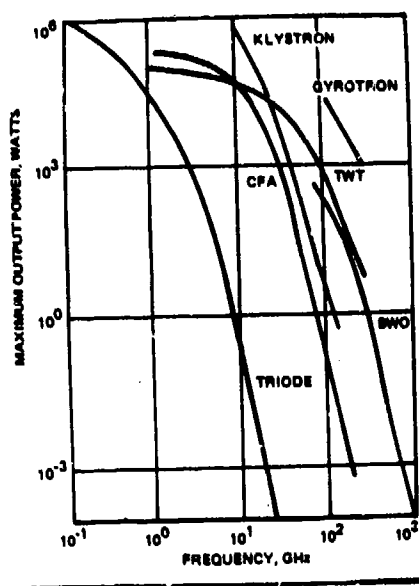
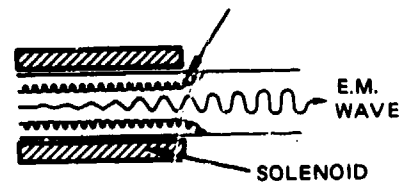


FIGURE 13 SUMMARY OF THE PERFORMANCE OF VARIOUS VACUUM TUBES AS A FUNCTION OF FREQUENCY

E-BEAM GEN.
HOLLOW BEAM
 $W_L \gg W_H$
 $\Delta W_L / W_L \ll 1$



$$\beta = v/c$$

$$\gamma = (1 - \beta^2)^{-1/2}$$

$$\omega_{ce} = \frac{eB_0}{m_0\gamma}$$

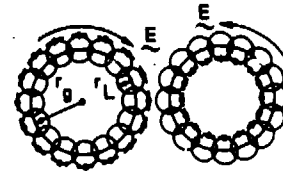


FIGURE 14 SCHEMATIC SHOWING THE PRINCIPLE OF OPERATION OF THE GYROTRON TUBE, IN WHICH THE TRANSVERSE ENERGY OF A RELATIVISTIC ELECTRON BEAM UNDERGOING CYCLOTRON ORBITS COUPLES TO AN EM WAVE

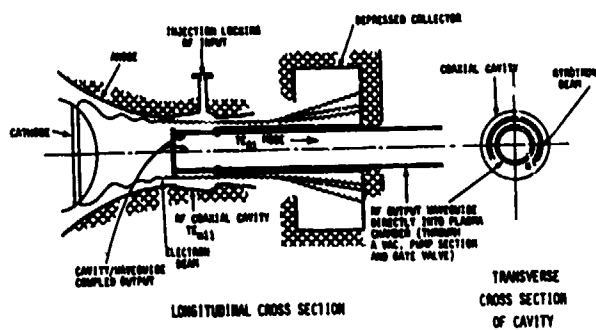


FIGURE 15 SCHEMATIC OF A GYROTRON AMPLIFIER SHOWING THE CATHODE WHICH GENERATES THE HOLLOW ELECTRON BEAM, THE INTERACTION REGION AND THE COLLECTOR

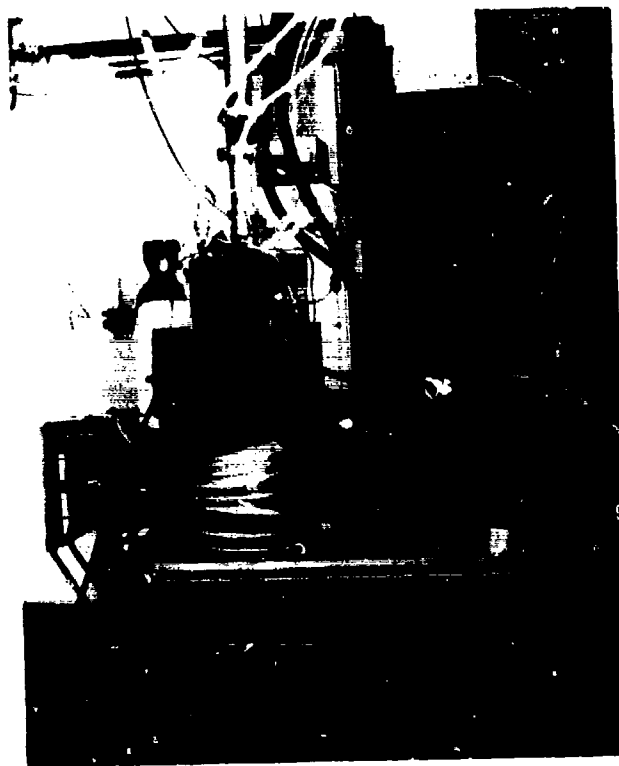


FIGURE 16 THE 28 GHz PULSED GYROTRON IN USE AT CULHAM

Power Output	25 - 65 kw Peak
Power Gain	40 - 30 dB
Frequency	28 GHz
Cyclotron Harmonic	Fundamental
Magnetic Field	11 kG
Beam Voltage	80 kV
Beam Current	8 A
Efficiency	10 %
Bandwidth	0.2%
Duty Factor	5%

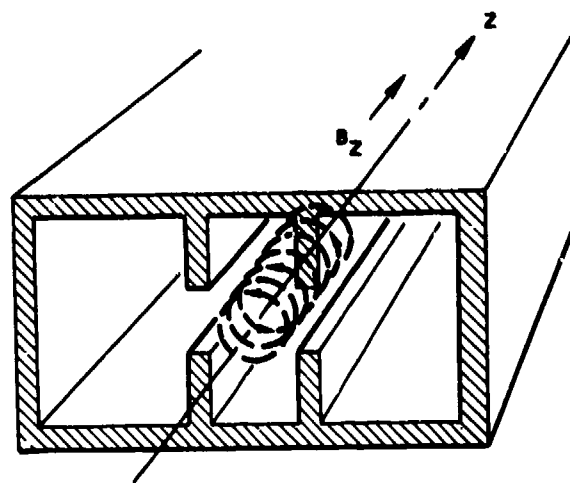


FIGURE 17 PERFORMANCE CHARACTERISTICS OF THE CULHAM GYROTRON

FIGURE 18 DOUBLE RIDGED WAVEGUIDE STRUCTURE OF THE PENIOTRON TUBE WHICH IS PREDICTED TO HAVE A VERY HIGH CONVERSION EFFICIENCY FOR TRANSVERSE BEAM ENERGY

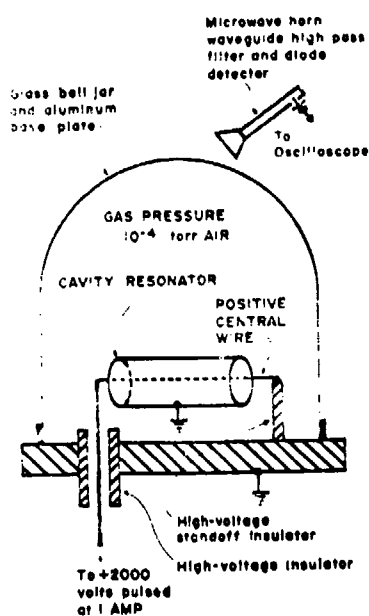


FIGURE 19 SCHEMATIC OF THE ORBITRON, WHICH USES A LOW PRESSURE GAS DISCHARGE AND HAS DEMONSTRATED POWER UP TO 50 GHz

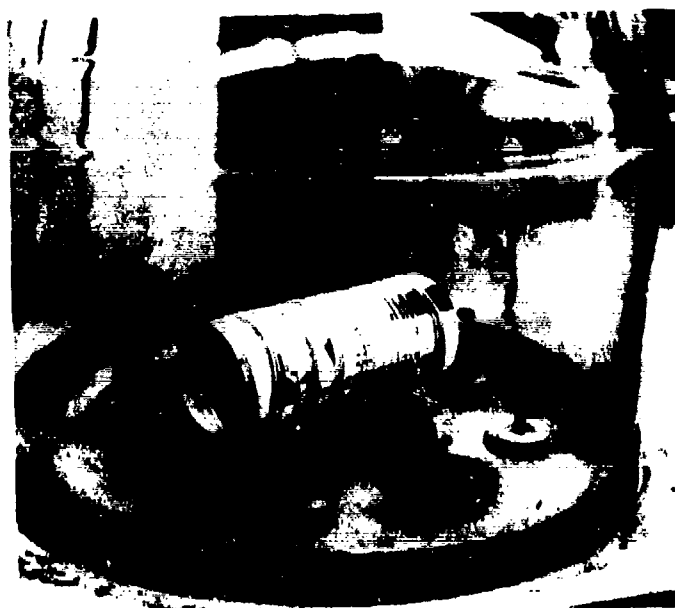


FIGURE 20 THE ORBITRON WAS DEMONSTRATED USING AN EMPTY ALUMINIUM BEER CAN AND HAS THE ADVANTAGE OF USING ELECTROSTATIC FIELDS ONLY WITH NO MAGNETS REQUIRED

LABORATORY CW POWER PERFORMANCE OF MICROWAVE DIODE vs. FREQUENCY

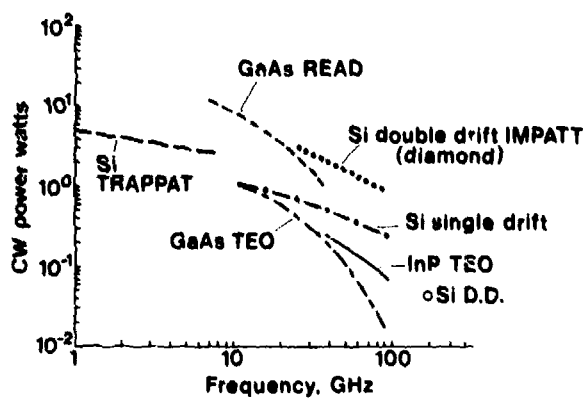


FIGURE 21 LABORATORY CW POWER PERFORMANCE OF MICROWAVE DIODES vs. FREQUENCY

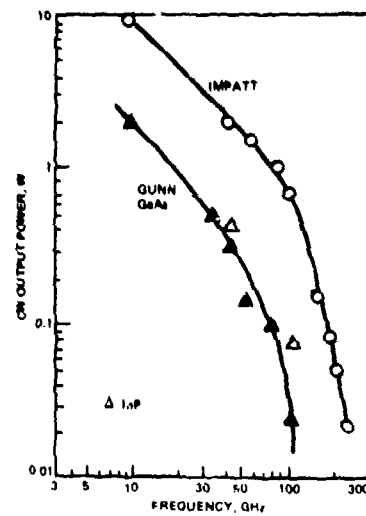


FIGURE 22 POWER OUTPUT vs. FREQUENCY FOR THE TWO PRINCIPAL TYPES OF SOLID STATE DEVICE :- SI DOUBLE DRIFT IMPATT DIODES ON DIAMOND HEAT SINKS AND InP AND GaAs TRANSVERSE ELECTRON DIODES ON COPPER HEAT SINKS

InP mm WAVE ACTIVE MULTIPLIER

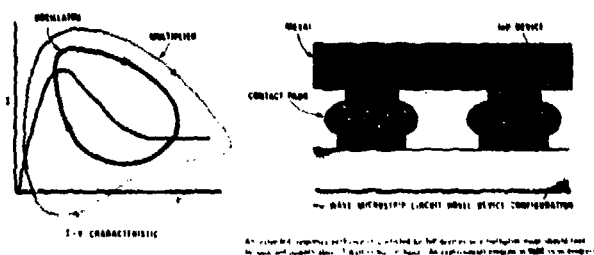


FIGURE 23 AN EXTENDED FREQUENCY PERFORMANCE PREDICTED FOR InP DEVICES IN MULTIPLIER MODE SHOULD LEAD TO GAIN AND POWER ABOVE 1W IN THE MILLIMETRE BAND

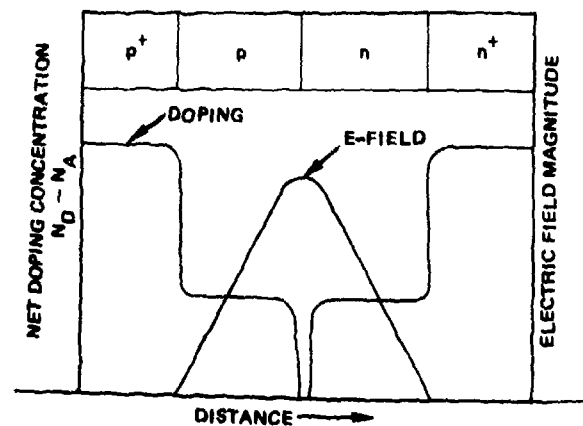


FIGURE 24 THE DOPING AND ELECTRIC FIELD PROFILE FOR DOUBLE DRIFT IMPATT DEVICES

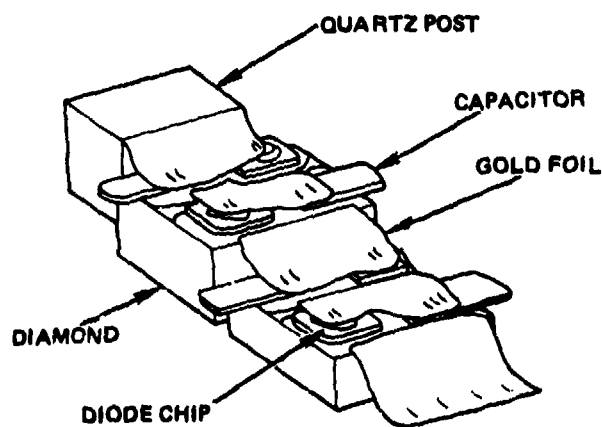


FIGURE 25 SKETCH OF A 4-CHIP 60W PULSED IMPATT DIODE ASSEMBLY

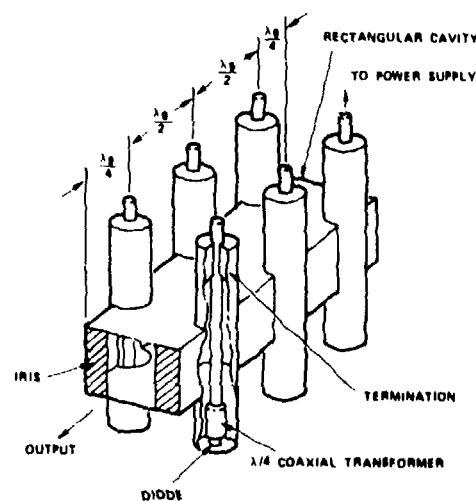


FIGURE 26 POWER COMBINER USING RECTANGULAR RESONATOR